



**UNIVERSITI PUTRA MALAYSIA**

**DEVELOPMENT OF A CRISP FUZZY-LIKE CONTROLLER USING  
FORMULA-BASED AND VECTORIZED APPROACHES**

**MOHAMMAD KARIMADINI.**

**FK 2006 51**

**DEVELOPMENT OF A CRISP FUZZY-LIKE CONTROLLER USING  
FORMULA-BASED AND VECTORIZED APPROACHES**

**By**

**MOHAMMAD KARIMADINI**

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in  
Fulfilment of Requirement for the Degree of Master of Science**

**May 2006**



**DEVELOPMENT OF A CRISP FUZZY-LIKE CONTROLLER USING  
FORMULA-BASED AND VECTORIZED APPROACHES**

**By**

**MOHAMMAD KARIMADINI**

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in  
Fulfilment of Requirement for the Degree of Master of Science**

**May 2006**



Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

**DEVELOPMENT OF A CRISP FUZZY-LIKE CONTROLLER USING  
FORMULA-BASED AND VECTORIZED APPROACHES**

By

**MOHAMMAD KARIMADINI**

**May 2006**

**Chairman: Mohammad Hamiruce Marhaban, PhD**

**Faculty: Engineering**

Simplifying of implementation of linear state feedback fuzzy controllers is investigated through the thesis. One of the most important problems in fuzzy controller design is the number of fuzzy subsets (membership functions) for each fuzzy input/output variable. The number of fuzzy subsets and consequently the number of fuzzy rules should be big enough to achieve good approximation of control surface and have a smooth and robust control. However as the number of rules increases, the memory space, and program cycle time and total project cost will also increase dramatically.

The thesis proposes crisp-fuzzy like controller derived by two novel approaches. The first one which is formula based crisp fuzzy-like controller proves that the monotonic fuzzy controller is similar to nonlinear saturated controller and then represents several different controller formulas. The second controller namely vectorized crisp fuzzy –like controller maps the fuzzy variables in a vectorial space and derives formula that has the structure similar to PID controllers. The proposed controllers are inspired from fuzzy

logic where they can express the control law semantically but they are absolutely crisp. Consequently the needed memory space is minimized since the rule table has been replaced with the formula. On the other hand fuzzy controllers have high computational complexity while the new controllers are very simple to design, tune and implement. Some new performance indexes also are proposed to evaluate the performance and stability of different controllers. Several well-known industrial models are used for simulation and a dimmer circuit to control the bulb temperature, has been used as a case study. Both simulation and experimental results show that the crisp fuzzy-like controllers have the same or in some cases better performance and stability compared with the conventional fuzzy logic controllers, with extra merits of lower memory space and cycle time.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia  
sebagai memenuhi keperluan untuk ijazah Master Sains

**PENGAWAL SEAKAN SAMAR YANG JITU BERDASARKAN FORMULA  
DAN PENDEKATAN PEMVEKTORAN**

Oleh

**MOHAMMAD KARIMADINI**

**Mei 2006**

**Pengerusi: Mohammad Hamiruce Marhaban, PhD**

**Fakulti: Kejuruteraan**

Mempermudahkan pelaksanaan pengawal samar suapbalik keadaan lurus adalah dikaji selidik melalui tesis ini. Salah satu daripada masalah penting di dalam rekabentuk pengawal samar adalah bilangan subset-subset samar (fungsi-fungsi keahlian) untuk setiap pembolehubah input/output samar. Bilangan subset samar dan seterusnya bilangan aturan samar mestilah besar dan mencukupi bagi mencapai anggaran permukaan kawalan yang baik dan mempunyai kawalan yang lancar dan berdaya tahan. Namun demikian, penambahan bilangan aturan telah menyebabkan penambahan secara mendadak terhadap ruang memori, masa kitaran pentaturcaraan dan jumlah kos projek

Tesis ini mencadangkan pengawal seakan-samar jitu yang dihasilkan dari dua pendekatan yang novel. Yang pertama iaitu pengawal seakan-samar jitu berasaskan formula membuktikan bahawa pengawal samar yang bersifat monotonik adalah serupa dengan pengawal tepu lurus dan seterusnya mewakili beberapa formula pengawal yang berlainan. Pengawal yang kedua iaitu pengawal seakan-samar jitu yang bervektor, memetai pembolehubah samar di dalam ruang vector dan menghasilkan formula yang mempunyai struktur serupa dengan pengawal PID. Pengawal-pengawal yang

dicadangkan adalah diinspirasi dari logik samar tetapi mereka adalah jitu dimana mereka mampu mempersembahkan aturan pengawal secara semantik. Seterusnya ruang memori yang diperlukan adalah dikurangkan oleh kerana jadual aturan telah digantikan dengan formula. Sebaliknya, pengawal samar mempunyai kerumitan linguistik berkomputer yang tinggi, manakala pengawal yang baru adalah amat mudah untuk merekabentuk, tiun dan melaksana. Beberapa indeks pencapaian baru juga dicadangkan bagi menilai prestasi dan kestabilan pelbagai pengawal. Beberapa model-model industri yang mayshur digunakan dalam simulasi dan litar pemalap untuk mengawal suhu buih telah digunakan sebagai pembelajaran kes. Kedua-duanya, simulasi dan keputusan eksperimen menunjukkan bahawa pengawal seakan-samar jitu mempunyai prestasi dan kestabilan yang sama atau di dalam kes-kes yang tertentu lebih baik jika dibandingkan dengan pengawal logic samar konvensional, dengan kelebihan mempunyai ruang memori yang kecil dan masa kitaran yang kurang.

## ACKNOWLEDGMENTS

In the name of Allah, the Most gracious, the Most merciful.

First and foremost, I would like to express my gratitude to Allah, for giving free will and strength to complete my project.

I would like to convey all my sincere thanks to my supervisor Dr. Mohammad Hamiruce Marhaban. The thesis would not have been done without his support, encouragement and comments. Thanks and appreciation is extended to the members of the supervisory committee Associate Prof. Dr. Ishak Aris and Dr. Samsul Bahari Mohd Noor and also to my good lecturer Associate Prof. Dr. Abubakar Ghazali for providing the equipments of the case study and for spending his valuable time and information to help me.

My special thanks to the members of engineering faculty and GSO of Universiti Putra Malaysia for their helps.

My greatest thanks go to my mother and my deceased father how always have encouraged and believed in me. Thanks all my brothers, sisters, parents in law and entire family. My final thanks are for my wife and my sons the source of my inspiration.

Peace and blessing upon prophet Mohammad (s.t.w.).



## ACKNOWLEDGMENTS

In the name of Allah, the Most gracious, the Most merciful.

First and foremost, I would like to express my gratitude to Allah, for giving free will and strength to complete my project.

I would like to convey all my sincere thanks to my supervisor Dr. Mohammad Hamiruce Marhaban. The thesis would not have been done without his support, encouragement and comments. Thanks and appreciation is extended to the members of the supervisory committee Associate Prof. Dr. Ishak Aris and Dr. Samsul Bahari Mohd Noor and also to my good lecturer Associate Prof. Dr. Abubakar Ghazali for providing the equipments of the case study and for spending his valuable time and information to help me.

My special thanks to the members of engineering faculty and GSO of Universiti Putra Malaysia for their helps.

My greatest thanks go to my mother and my deceased father how always have encouraged and believed in me. Thanks all my brothers, sisters, parents in law and entire family. My final thanks are for my wife and my sons the source of my inspiration.

Peace and blessing upon prophet Mohammad (s.t.w.).

I certify that an Examination Committee has met on 15 May 2006 to conduct the final examination of Mohammad Karimadini on his Master of Science thesis entitled “Development of a Crisp Fuzzy-like Controller using Formula-based and Vectorized Approaches” in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

**Norman Marium, PhD**

Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Chairman)

**Senan Mahmod Abdullah, PhD**

Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Internal Examiner)

**Norhisam Misron, PhD**

Lecturer  
Faculty of Engineering  
Universiti Putra Malaysia  
(Internal Examiner)

**Rubiyah Yusof , PhD**

Associate Professor  
Faculty of Engineering  
Universiti Teknologi Malaysia  
(External Examiner)



---

**HASANAH MOHD. GHAZALI, PhD**

Professor/Deputy Dean  
School of Graduate Studies  
Universiti Putra Malaysia

Date : 11 JUL 2006

I certify that an Examination Committee has met on 15 May 2006 to conduct the final examination of Mohammad Karimadini on his Master of Science thesis entitled “Development of a Crisp Fuzzy-like Controller using Formula-based and Vectorized Approaches” in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

**Norman Marium, PhD**

Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Chairman)

**Senan Mahmod Abdullah, PhD**

Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Internal Examiner)

**Norhisam Misron, PhD**

Lecturer  
Faculty of Engineering  
Universiti Putra Malaysia  
(Internal Examiner)

**Rubiyah Yusof , PhD**

Associate Professor  
Faculty of Engineering  
Universiti Teknologi Malaysia  
(External Examiner)



---

**HASANAH MOHD. GHAZALI, PhD**

Professor/Deputy Dean  
School of Graduate Studies  
Universiti Putra Malaysia

Date : 11 JUL 2006

This thesis submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee are as follows:

**Mohammad Hamiruce Marhaban, PhD**

Lecturer

Faculty of Engineering

Universiti Putra Malaysia

(Chairman)

**Ishak Aris, Ph.D.**

Associate Proffesor

Faculty of Engineering

Universiti Putra Malaysia

(Member)

**Samsul Bahari Mohd. Noor , PhD**

Lecturer

Faculty of Engineering

Universiti Putra Malaysia

(Member)



---

**AINI IDERIS, PhD**

Professor/ Dean

School of Graduate Studies

Universiti Putra Malaysia

Date: 10 AUG 2006

This thesis submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee are as follows:

**Mohammad Hamiruce Marhaban, PhD**

Lecturer

Faculty of Engineering

Universiti Putra Malaysia

(Chairman)

**Ishak Aris, Ph.D.**

Associate Proffesor

Faculty of Engineering

Universiti Putra Malaysia

(Member)

**Samsul Bahari Mohd. Noor , PhD**

Lecturer

Faculty of Engineering

Universiti Putra Malaysia

(Member)



---

**AINI IDERIS, PhD**

Professor/ Dean

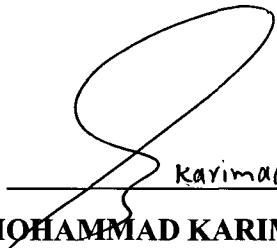
School of Graduate Studies

Universiti Putra Malaysia

Date: 10 AUG 2006

## DECLARATION

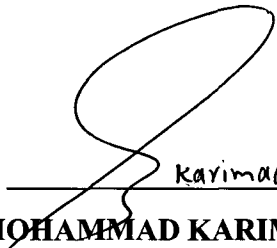
I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

  
\_\_\_\_\_  
Karimadini  
**MOHAMMAD KARIMADINI**

Date: 10 JUL 2006

## DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

  
\_\_\_\_\_  
Karimadini  
**MOHAMMAD KARIMADINI**

Date: 10 JUL 2006

## TABLE OF CONTENTS

	<b>ABSTRACT</b>	<b>Page</b>
	<b>ABSTRAK</b>	ii
	<b>ACKNOWLEDGEMENTS</b>	iv
	<b>APPROVAL</b>	vi
	<b>DECLARATION</b>	vii
	<b>LIST OF TABLES</b>	ix
	<b>LIST OF FIGURES</b>	xiii
		xiv
<b>CHAPTER</b>		
1	<b>INTRODUCTION</b>	1
1.1	Introduction	1
1.1.1	Background Overview	1
1.1.2	Benefit of Fuzzy Controllers	4
1.1.3	Fuzzy Controller Design Procedures	8
1.2	Problem Statement	10
1.3	Objectives and Project Interests	11
1.4	Outline of the Thesis and Contributions	12
1.5	The Scope of Work	13
2	<b>LITERATURE REVIEW</b>	14
2.1	PID Controller	14
2.2	Fuzzy Logic	16
2.2.1	Soft Computing, Fuzzy Logic, Computing With Words	16
2.2.2	Fuzzy Logic Theory	17
2.2.3	Fuzzy Logic Control	18
2.2.4	Justification of Fuzzy Control Rules	20
2.2.5	Types of Fuzzy Control Rules	22
2.2.6	Properties of Rule Base	24
2.2.7	Fuzzy Controller Analysis	25
2.3	Fuzzy PID Controller	30
2.3.1	Mamdani Fuzzy PID Controllers with Nonlinear Input Fuzzy Sets	30
2.3.2	Practical Design Method for Fuzzy PID Control from Conventional PID Control	33
2.4	Tuning of Fuzzy PID Controllers Using Fuzzy Logic	37
2.4.1	Proportional Control	38
2.4.2	Proportional-Derivative Controller	39
2.4.3	Incremental Control	40
2.4.4	Proportional, Integral and Derivative Control	42
2.4.5	FLC-PID with Linear Defuzzification Method	48
2.4.6	FLC-PID with Non-Linear Defuzzification Method	48





## TABLE OF CONTENTS

	<b>ABSTRACT</b>	<b>Page</b>
	<b>ABSTRAK</b>	ii
	<b>ACKNOWLEDGEMENTS</b>	iv
	<b>APPROVAL</b>	vi
	<b>DECLARATION</b>	vii
	<b>LIST OF TABLES</b>	ix
	<b>LIST OF FIGURES</b>	xiii
		xiv
<b>CHAPTER</b>		
1	<b>INTRODUCTION</b>	1
1.1	Introduction	1
1.1.1	Background Overview	1
1.1.2	Benefit of Fuzzy Controllers	4
1.1.3	Fuzzy Controller Design Procedures	8
1.2	Problem Statement	10
1.3	Objectives and Project Interests	11
1.4	Outline of the Thesis and Contributions	12
1.5	The Scope of Work	13
2	<b>LITERATURE REVIEW</b>	14
2.1	PID Controller	14
2.2	Fuzzy Logic	16
2.2.1	Soft Computing, Fuzzy Logic, Computing With Words	16
2.2.2	Fuzzy Logic Theory	17
2.2.3	Fuzzy Logic Control	18
2.2.4	Justification of Fuzzy Control Rules	20
2.2.5	Types of Fuzzy Control Rules	22
2.2.6	Properties of Rule Base	24
2.2.7	Fuzzy Controller Analysis	25
2.3	Fuzzy PID Controller	30
2.3.1	Mamdani Fuzzy PID Controllers with Nonlinear Input Fuzzy Sets	30
2.3.2	Practical Design Method for Fuzzy PID Control from Conventional PID Control	33
2.4	Tuning of Fuzzy PID Controllers Using Fuzzy Logic	37
2.4.1	Proportional Control	38
2.4.2	Proportional-Derivative Controller	39
2.4.3	Incremental Control	40
2.4.4	Proportional, Integral and Derivative Control	42
2.4.5	FLC-PID with Linear Defuzzification Method	48
2.4.6	FLC-PID with Non-Linear Defuzzification Method	48



2.5	Comparative Fuzzy Controller Assessment	49
2.6	Fuzzy State Feedback Controller	53
2.6.1	Conditions on General Mamdani Fuzzy Controllers as Nonlinear, Variable Gain State Feedback Controllers with Stability Analysis	53
2.6.2	General Mamdani Fuzzy Controller	54
2.7	Linear Fuzzy Controller	58
2.8	Formulation of Fuzzy controllers	58
2.9	Summary	62
3	<b>METHODOLOGY</b>	63
3.1	Crisp Fuzzy-Like Controller: Formula-Based Approaches	64
3.1.1	Introduction	64
3.1.2	Extension of PD-Like Fuzzy Controller	66
3.2	Crisp Fuzzy-Like Controller: Vectorized Approaches	98
3.2.1	Projected Vectorized Crisp Fuzzy-Like Controller	98
3.2.2	Canonical -PD Vectorized Crisp Fuzzy-Like Controller	103
3.3	Summary	104
4	<b>SIMULATION AND EXPERIMENTAL RESULTS</b>	109
4.1	Simulation Results	109
4.1.1	DC Motor System	110
4.1.2	First-Order Nonlinear System	113
4.1.3	First-Order Non-Minimum Phase System	115
4.1.4	Second-Order Non-Minimum Phase System	117
4.1.5	Third-Order Non-Minimum Phase System	119
4.1.6	Liquid Level System	121
4.1.7	Servo Motor System	123
4.1.8	Second-Order Unstable Nonlinear System	126
4.1.9	Discussion on Simulation Results	128
4.1.10	Comparison	134
4.2	Experimental Results	142
4.2.1	Experimental Setup	142
4.2.2	Experimental Plots	147
4.2.3	Discussion	153
4.3	Summary	165
5	<b>CONCLUSION AND SUGGESTION FOR FUTURE WORK</b>	167
5.1	Conclusion	167
5.2	Recommendation for Future Work	168
	<b>REFERENCES</b>	170
	<b>APPENDIX</b>	177
	<b>BIODATA OF THE AUTHOR</b>	184

## LIST OF TABLES

Tables	Page
2.1	Effects of independent P, I and D tuning 15
2.2	Fuzzy control rules used by the two-dimensional fuzzy controller 33
2.3	Linear fuzzy PI control rule base with $3 \times 3$ partitions 35
2.4	Linear fuzzy PD control rule base with $3 \times 3$ partitions 35
2.5	Compare of different types of fuzzy controllers 43
2.6	Relationship between fuzzy and PID gains 43
2.7	PID parameters according to the Zeigler-Nichols frequency response method 46
2.8	Relationship between the scaling factors of the MHPI-FLC and the gains of its traditional counterpart 46
2.9	Effects of the scaling factors on speed and stability 47
2.10	Influence of scale factors variation on control performance 49
2.11	Basic rules table of the fuzzy module 52
2.12	Meaning of the linguistic variables in the fuzzy module 52
3.1	Rule table (number of rules $= 7 \times 7 = 49$ ) 65
3.2	Numerical assigned rule table for PD-like fuzzy controller in a forward Process 71
3.3	The comparison of granular and numerical notations of rule table 74
4.1	Legend of plot colors and styles 110
4.2	Experimental results of dimmer circuit case study to control of the temperature using controller algorithms as Equations (4.1- 4.8) 164

## LIST OF FIGURES

Figures		Page
1.1	Block Diagram of a Fuzzy Controller	7
2.1	Block diagram representation of a PID controller	15
2.2	Membership functions of the terms “full legal age” and “adult”	18
2.3	Basic configuration of fuzzy logic controller (FLC)	19
2.4	Rule justification by using phase plane (a)Phase –plane trajectory. (b)System step response	21
2.5	A whole overlaps parameter evaluation	26
2.6	A typical trajectory of rules firing for a stable system	28
2.7	A typical trajectory of rules firing for an unstable system	28
2.8	The fuzzification membership function of linear-like fuzzy logic controller	34
2.9	Linear-like fuzzy PI controller surface	35
2.10	PI and fuzzy PI control results on the third-order system	36
2.11	Fuzzy Proportional Controller (FP)	39
2.12	Fuzzy PD controller (FPD)	39
2.13	Fuzzy incremental controller (FInc)	41
2.14	Fuzzy PD+I Controller (FPD+I)	42
2.15	Structures for (a) PI-FLC, (b) PD-FLC, and (c) PID-FLC	44
2.16	PI+PD-FLC structures for (a) PID-FLC, (b) HPID-FLC	45
2.17	Modified HPID-FLC (MHPID-FLC) structure	46
2.18	Fuzzy-PID controller and tuning parameters	47

2.19	The two-degrees-of-freedom structure of the PID controller with set-point weighting	51
2.20	Two examples of piecewise linear fuzzy sets	56
2.21	A fuzzy set and its respective center of gravity below	59
2.22	A linear two-dimensional rule base and its VSC feature	60
2.23	Functional composition of the inference cell $I_c(i, j)$	60
3.1	Flowchart of the methodology	63
3.2	Triangular and Gaussian Examples of fuzzy controller membership functions	66
3.3	Closed loop PD control system block diagram	67
3.4	Big and small errors and required control signals	69
3.5	$e_n$ , $\Delta e_n$ and $U_n$ membership functions in normalized universe of discourse	72
3.6	Graph $C(U_n(i, j)) = f(C(e_n(i)), C(\Delta e_n(j)))$ as Equation (3.16)	75
3.7	Forward control output surface $C(U_n(i, j)) = f(C(e_n(i)), C(\Delta e_n(j)))$ in three dimensional space as Equation (3.16)	76
3.8	Reverse control output surface $C(U_n(i, j)) = f(C(e_n(i)), C(\Delta e_n(j)))$ in three dimensional space as Equation (3.16)	76
3.9	Normalized support with $n=2k+1$ fuzzy terms	77
3.10	$Min(\mu_1(x), \mu_2(x))$ and $Max(\mu_1(x), \mu_2(x))$	78
3.11	Different whole overlap ratios	79
3.12	PD-like fuzzy equivalent controller	82
3.13	Illustration of formula of PD-like fuzzy equivalent controller with absolute function	83

3.14	Illustration of formula of PD-like fuzzy equivalent controller constructed with ramp functions	84
3.15	Two dimensional graph of hyperbolic PD-like fuzzy equivalent controller	87
3.16	Three dimensional graph of hyperbolic PD-like fuzzy equivalent controller	87
3.17	$\tan(\theta)$ is the maximum slop of $y(x) = \tanh(K_p \times x)$	88
3.18	Smooth ON/OFF controller	90
3.19	Hyperbolic controller function using sigmoid function	91
3.20	Exponential function controller	93
3.21	Quadratic function controller	94
3.22	Sinusoidal function Controller	95
3.23	Sin-Absolute function controller	96
3.24	atan function controller	97
3.25	Normalized vectorial Sum	99
3.26	Projected normalized vectorial sum examples	100
4.1	Step response of DC motor system	112
4.2	Process output, Control output, error and change of error of closed loop control system for DC motor using Equations (4.1)- (4.8) as controller algorithm	113
4.3	Step response of nonlinear fist-order nonlinear model	114
4.4	Process output, Control output, error and change of error of closed loop control system for “first-order nonlinear” model using Equations (4.1)-(4.8) as controller algorithm	115
4.5	Discrete step response of first –order non-minimum phase system	116
4.6	Process output, Control output, error and change of error of closed -loop control system for “first-order non minimum phase” model using Equations (4.1)-(4.8) as controller algorithm	117

4.7	Step response of “second –order non-minimum phase” system	118
4.8	Process output, Control output, error and change of error of closed loop control system for “second-order non minimum phase” model using Equations (4.1)-(4.8) as controller algorithm	119
4.9	Step response of “third –order non-minimum phase” system	120
4.10	Process output, Control output, error and change of error of closed loop control system for “third-order non minimum phase” model using Equations (4.1)-(4.8) as controller algorithm	121
4.11	Step response of “liquid level” system	122
4.12	Process output, Control output, error and change of error of closed loop control system for “liquid level” model using Equations (4.1)-(4.8) as controller algorithm	123
4.13	Servo motor schematic	123
2.14	Block diagram of the servo motor	124
4.15	Step response of “servo motor” system	125
4.16	Process output, Control output, error and change of error of closed loop control system for “servo motor” model using Equations (4.1)-(4.8) as controller algorithm	126
4.17	Step response of “second-order unstable nonlinear” system	127
4.18	Process output, Control output, error and change of error of closed loop control system for “second-order unstable nonlinear” model using Equations (4.1)-(4.8) as controller algorithm	128
4.19	An example of Process control	130
4.20	Comparison of control performance and stability characteristics of DC motor model for controllers with Equations (4.1) – (4.8)	135
4.21	Comparison of control performance and stability characteristics of first-order nonlinear model for controllers with Equations (4.1) – (4.8)	135
4.22	Comparison of control performance and stability characteristics of First-order non-minimum phase model for controllers with Equations (4.1) – (4.8)	136

4.23	Comparison of control performance and stability characteristics of second-order non-minimum phase model for controllers with Equations (4.1) – (4.8)	136
4.24	Comparison of control performance and stability characteristics of third-order non-minimum phase model for controllers with Equations (4.1) – (4.8)	137
4.25	Comparison of control performance and stability characteristics of liquid level model for controllers with Equations (4.1) – (4.8)	137
4.26	Comparison of control performance and stability characteristics of servo motor model for controllers with Equations (4.1) – (4.8)	138
4.27	Comparison of control performance and stability characteristics of second-order unstable nonlinear model for controllers with Equations (4.1) – (4.8)	138
4.28	An example of front panel window in LabVIEW program	143
4.29	An example of block diagram window in LabVIEW program	144
4.30	Block diagram of the light dimmer system	145
4.31	Light dimmer circuitry	146
4.32	Hardware configuration of experimental result	147
4.33	Control results of dimmer circuit in terms of control algorithm #1	149
4.34	Control results of dimmer circuit in terms of control algorithm #2	149
4.35	Control results of dimmer circuit in terms of control algorithm #3	150
4.36	Control results of dimmer circuit in terms of control algorithm #4	150
4.37	Control results of dimmer circuit in terms of control algorithm #5	151
4.38	Control results of dimmer circuit in terms of control algorithm #6	151
4.39	Control results of dimmer circuit in terms of control algorithm #7	152
4.40	Control results of dimmer circuit in terms of control algorithm #8	152
4.41	Step response and ZPplot of the dimmer process for controller #1	154



4.42	Step response and ZPplot of the dimmer process for controller #2	155
4.43	Step response and ZPplot of the dimmer process for controller #3	155
4.44	Step response and ZPplot of the dimmer process for controller #4	156
4.45	Step response and ZPplot of the dimmer process for controller #5	156
4.46	Step response and ZPplot of the dimmer process for controller #6	157
4.47	Step response and ZPplot of the dimmer process for controller #7	157
4.48	Step response and ZPplot of the dimmer process for controller #8	158
4.49	An example of two different controlled values	159